An alternative methodology for Machine Tool Error determination through workpiece measurement.

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Abstract
Error measurement and compensation in machine tools have always been a subject of interest for the researchers. Much work has been done regarding the measurement of individual errors in a machine tool and different approaches have been adopted throughout the existing literature. While researchers tend to measure the differences in actual and obtained position of a machine tool through use of devices such as laser-interferometer and ball-bar, significant research has also been done towards measurement of errors through use of metrology feedback techniques. Progress has also been made in the existing literature towards error determination, mainly positional, and compensation through workpiece measurement.
There is, however, a need for a comprehensive error profiling methodology using the workpiece measurement method. The current research presents a new methodology for error determination through workpiece measurement on a Coordinate Measuring Machine (CMM), where a specially designed workpiece is to be machined on a 3 Axis machining center, under various conditions with each condition targeting different types of error. The scope of the research includes the determination of all errors including thermal, positional and dynamic errors. Such a method lowers the cost of error determination while also providing a shop-floor-friendly error determination technique.
Keywords
Error identification, workpiece measurement, metrology feedback, thermal error measurement, dynamic error measurement.

1. Introduction

The extensive use of CNC machines in industry and the demand for higher accuracies have increased the importance of error identification and compensation in such machines. Driven by the high demand several different techniques have been utilized for error identification and compensation. These approaches range from use of specialized equipment such as laser interferometer to the use of FEM models for error prediction. It is important to emphasise here that the most accurate error profile is usually obtained through actual cutting of the material or through actual tool moments. This has led to the use of techniques for error identification through metrology feedback. The metrology feedback includes processes using probing of an artifact or workpiece or a combination of both to provide the errors in machine tool under consideration. One such methodology that combines use of artefact probing with probing of a machined workpiece has been presented by [1]. A similar method has also been reported by [2].

Another article [3] has presented research that includes the error identification through measurement of the workpiece after machining. The authors first modelled the kinematic errors of a five-axis machining centre followed by a machining procedure definition to include all the required errors. The machining has been performed at different conditions defined by positions of rotary tilting table and linear axis. Meanwhile, a machining test and workpiece measurement based error analysis techniques for evaluating the kinematic errors on five axis machining centre has been presented by [4]. Work has also been done towards the workpiece design for such evaluations, such designs can be found in the articles discussed earlier while [5] have presented a new test part for identification of the performance of 5 axis machining centre.

The error identification through workpiece machining is a simpler process that has the advantage of being applicable in the general manufacturing environment. The major reason for this is the availability of CMM which is used in such measurements. Meanwhile equipment's such as tracking interferometers are not generally available in machine shops due to their limited scope of usage in such environments. Although the error profiling has been carried out based on the position of axis and the corresponding effects on the error magnitude in most studies, the errors in time domain, thermal errors, errors due to controller and other feed and force related errors needs to be extensively studied.

The current research therefore focuses towards the development and application of a new methodology for identification of kinematic, thermal and dynamic errors for a three-axis machining centre with the difference from existing research that the time and machining parameter dependant errors have also been identified within the same model. A workpiece is machined in three separate setups with different set of conditions and the final geometry of the workpiece is measured to obtain the error magnitudes at each condition. The overall error magnitudes are than processed to obtain individual error magnitudes through comparison multiple regressions. Along with the overall error identification model, part design for such identification and the experimental setup followed by results has also been made a part of the current research.

2. Proposed Methodology

The current methodology as stated earlier uses a three-axis machining center for experimentation. In the first phase a complete error model is developed based on the expected geometry of workpiece before and after machining. Three different set of cutting conditions based on time of machining, feed and speed are proposed for machining similar workpiece geometry. A fixture is used for mounting the workpiece. The machining of the workpiece and the measurement on CMM are all performed with the same mounting.

At first the workpiece is machined with each step machined at a different temperature state. In the first step the top surface is machined immediately after the machine start where the temperature state is taken as 'To'. For the subsequent steps the temperate state for both the spindle and the axis is changed through idle running of spindle at a specific speed for a specific time interval while for the table it is done through a specifically designed maneuver for the axis. The maneuver resembles the actual machining of the workpiece with no cutting. Same feed and spindle speeds are used for all steps for the first workpiece. Hence it can be safely assumed that the errors due to feed and spindle speed are similar in magnitude. The second setup of machining involves each step being machined at different feeds while the spindle speed is kept the same as that used for the first workpiece. In the third setup, the workpiece is machined with different spindle speeds at each step while keeping the feed same as that used for the first workpiece. Time interval during which each step is machined is observed for each setup.

This in turn provides a set of machined dimensions that have influence of either one or a combination of dynamic, kinematic and thermal errors. After each setup, the workpiece is taken to CMM along with the fixture and the profile is measured at predetermined points. The measured data points are than used towards calculations of different error magnitudes at the respective conditions. While some errors such as table tilt around X and Y axis are measured through comparison, the calculation of true magnitude of errors such as the overall change in spindle length with time and the dynamic error in all three-axis required a regression analysis of different errors. Section 2.2 presents the error modelling and the use of regression equations within the model. However, it is also important at this stage to discuss the workpiece and fixture design.

2.1. Workpiece and Fixture design:

The measurement of errors requires an experimental setup with appreciation for various factors such as accuracy, repeatability, traceability and flexibility towards consideration of all errors. The workpiece design is provided in Figure 1. Each step of the workpiece constitutes three different surfaces. This helps in determination of errors while also providing a uniform kinetic error magnitude. To introduce repeatability and to remove fixturing errors from the overall results, the workpiece is supplemented with a fixture to be used along the workpiece during the machining process and at the Coordinate Measuring machine (CMM). Along with the removal of fixturing errors this helps in removing any unnecessary deformation at the bottom surface which is to be taken as reference. The use of fixture in this regard was also found feasible through a finite element analysis that exhibited a considerably lesser deflection when the fixture was introduced into the setup. The workpiece design and analysis are shown in Figure 1.

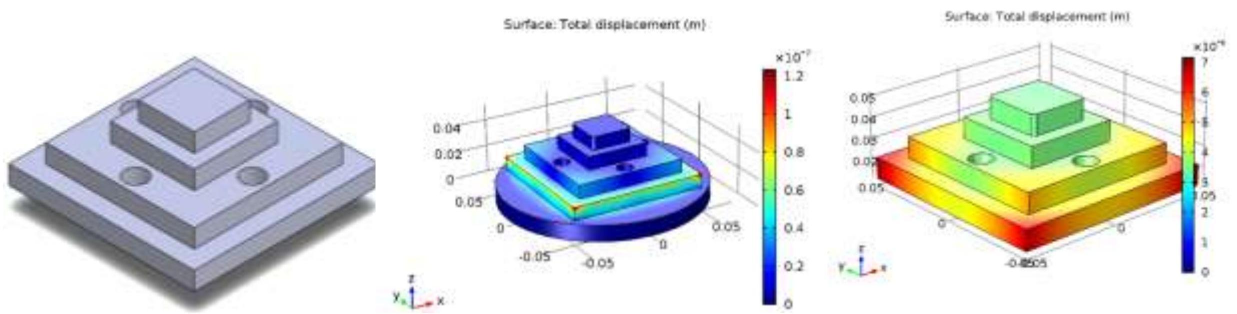

Figure 1 Workpiece design(left), Displacement of workpiece with(middle) and without(right) fixture.

2.2. Error definition and Modelling.

A specific set of dimensions are taken into consideration for each part and the errors are calculated through a set of equations that follow. Figure 2 shows the different workpiece dimensions under consideration.

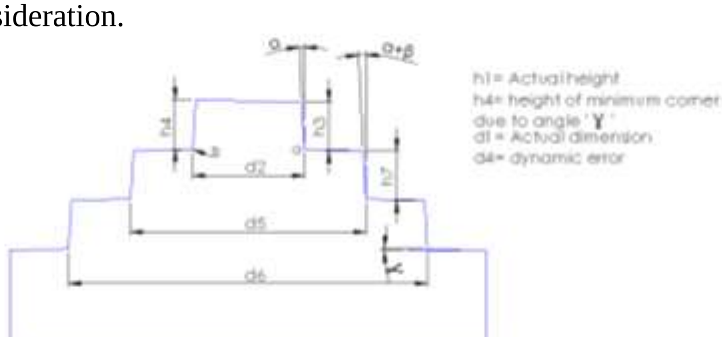

Figure 2 Final Dimensions of the workpiece after machining.

The dynamic error is first taken as zero based on the assumption that the machining parameters are relatively low hence generating a near zero error. This zero is however re-evaluated after every regression and the true value is incorporated in the final equations. The thermal errors and positional errors are than calculated based on this assumption. The governing equations for thermal errors are than used for the second work piece for calculating the thermal errors present at the time instance at which the surface is being machined. The overall feed based errors are than used to perform regression to obtain the equations for feed based errors. The error magnitude at the feed used in the first work piece are identified and than used in the thermal errors equation for providing the feed compensated value of thermal errors. New set of governing equations for thermal errors and subsequently the feed based errors are obtained through regression. The compensated equations are than further used to develop a spindle speed based error model using data from third work piece. The same compensation cycle is once again repeated for calculating all three error forms.

The method works similar as the root finding bisection method. Regression analysis is done through Minitab. A suitable regression model based on least error in prediction is chosen for every regression.

From Figure 2, The overall difference in dimensions of the workpiece due to control (e_c), thermal (e_{th}), positional (e_p) and dynamic errors (e_{dyn}) can be represented by equation 1.

$$d_1 = d_2 + e_p + 2\left(e_{th} + e_{dyn}\right) \tag{1}$$

Meanwhile at time t=0, the thermal errors are taken to be zero. Hence equation 1 can be rewritten as:

$$d_1 = d_2 + e_p + 2\left(e_{dyn}\right) \tag{2}$$

Similarly using trigonometric identities, the equations 3 and 4 can be obtained for the workpiece presented in Figure 2

$$d_3 = \frac{h_1 - h_4}{\tan\theta} \tag{3}$$

$$d_4 = \frac{h_3 - h_2}{\tan\theta} \tag{4}$$

The term ‘d4’ represents the dynamic error with the assumption that there is no position error at the starting, “zero” edge of the workpiece. After machining the steps at different temperature states the error due to spindle elongation noticed along x-axis can be represented as:

$$e_{spdx} = \alpha_x - (\alpha + \beta)_x \tag{5}$$

$$e_{ttx} = \theta_x - \gamma_x \tag{6}$$

$$e_{ptx} = (\mathrm{d}_{5x} - \mathrm{d}_{5xa} - e_{px} - (2.e_{dynx}))/2 \tag{7}$$

After thermal error evaluation and subsequent regression. A zero correction for thermal errors at the thermal zero stage is obtained and incorporated in the initial magnitude of respective positional errors. As the second workpiece machined at different feed rates for each surface at different machining time. The overall error equations are than given as:

$$e_{sdlfx} = h_{7x\prime} - h_{3x\prime} - e_{splzx} \tag{8}$$

Where the error due to increase in spindle length observed at x-axis is given by:

$$e_{splzx} = 0{,}0133031 * {'Temp\ state'} / (28{,}05 + {'Temp\ state'}) \tag{9}$$

The error in overall dimension due to change in feed is given as:

$$e_{ftx} = \theta_x - \gamma_x - e_{ttx} \tag{10}$$

$$e_{ttx} = 1 - 0{,}99 / ({'Temp\ state'}^{0{,}0222177}) \tag{11}$$

Similar set of equations are obtained for Y axis. It is important to notice that some of the errors such as the thermal tilt observed at X axis (e_{ttx}) and error due to spindle and cutter deflection under feed force (e_{spdfx}) are calculated in terms of angles. This will in turn provide a compensation with appreciation of the part dimensions. The error due to increase in spindle length along Z axis at any time instant is obtained through incorporating the equations for dynamic error into the equation for thermal error.

3. Machining test

The machining is carried out on Mazak three axis machining center. Aluminum 7071 is used as workpiece material while the fixture is developed using Stainless steel. Each workpiece is roughed out and the bottom surface of the workpiece is flattened using a face mill to provide a better contact surface with the fixture. The temperature state for the spindle is changed through running the spindle for 30 minutes at a spindle speed of 3500r.p.m. Meanwhile the table heating maneuver is performed at a feed rate of 100mm/min. The workpieces are machined using a 12 mm Carbide End mill. Spindle speed of 3500 r.p.m and feedrate of 100mm/min is used for machining the first workpiece. For the second and third workpiece, the feed rate is changed between 200 to 2000 mm/min and spindle speed was changed from 800 r.p.m to 5500 r.p.m. respectively. Figure 3 represents the machining and measurement setup.

Figure 3 Machining setup (Left), Measurement Setup (Right)

4. Results and discussion:

Figure 4 shows the magnitudes of different thermal errors and feed based changes in dynamic errors calculated through analysis of the dimensions of workpieces and after the required compensations for the initial assumptions through use of obtained data. Meanwhile figure 5 shows the dynamic errors and overall position and orientation errors of the individual axis. The dynamic errors observed are comparatively much smaller in magnitude than the thermal errors. However, it can be observed that there is almost zero surface tilt caused by changes in feed and speed. while the maximum increase in the individual step height obtained is also 0.0028mm in magnitude. One key aspect of the results is a set of equations obtained for prediction of thermal and dynamic errors based on time and Feed and speed respectively. Most dynamic and thermal errors can be predicted using the equations within an accuracy of 10%. The exceptions include *e_sdlfx* and *e_sdlsx*, i.e. the change in step height due to changes in feed and speed. In these cases, the accuracy of prediction ranges from 60-75%. Fig 5 further depicts the position and orientation errors of each individual axis. The orientation errors have been calculated in terms of degrees of table tilt exhibited at each axis. It is also important to mention here that for each individual set of calculation at least three different set of points have been used for ensuring the statistical significance of the results.

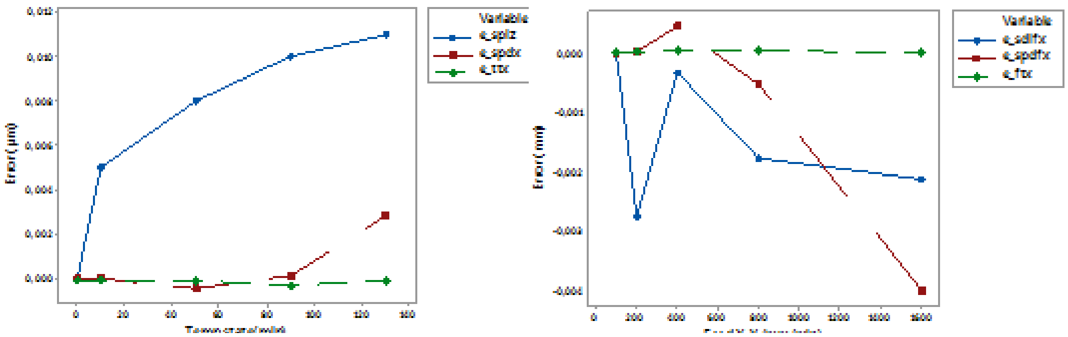

Figure 4 Thermal Errors (Left) and Feed based dynamic errors (Right)

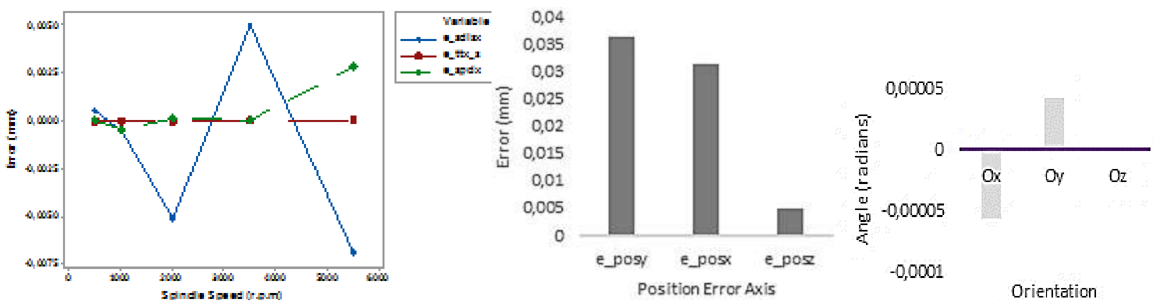

Figure 5 Speed Based Dynamic errors (Left) and Position Errors(Middle), Orientation Errors (Right)

5. Conclusion

A new methodology has been proposed for error identification through workpiece measurement. A combination of workpiece model and experiment design has been presented for error separation while a set of equations have also been proposed as the result of current study which can be used for real time part based error compensation. The kinetic errors identified through the methodology can be directly compensated in the controller while thermal and dynamic errors require either a G-code based compensation strategy which is feasible for large parts such as those machined in aerospace industry. The dynamic errors however may not be completely compensated yet a significant reduction in their magnitudes can be obtained through use of current methodology. The methodology presented is easy to follow at shop floor.

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